

Higgs two-gluon decay and the top-quark chromomagnetic moment

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Abstract

We obtain the effective interaction \mathcal{L}_{hgg} , which is driven by the fluctuations of the top quark, as a function of the top quark chromomagnetic factor κ_t . We show that for $\kappa_t \neq 2$ the Higgs-to-two gluon, $h \rightarrow gg$, decay rate is always significantly suppressed as compared to the standard case $\kappa_t = 2$, which would be contributing $\mathcal{O}(8.5\%)$ of the total Higgs decay width. We show that $h \rightarrow gg$ rate can vanish due to the negative interference with the bottom quark vacuum fluctuation amplitude. We discuss potential paths to obtain experimental information for the $h \rightarrow gg$ rate.

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Introduction: The Higgs-two-gluon coupling is an effective interaction originating in vacuum fluctuations of the top quark and to a lesser extent bottom quark. Consequently, the two gluon decay $h \rightarrow gg$ probes physical properties of the top quark, the heaviest standard model (SM) particle. The top chromomagnetic moment holds special interest because of the top's generally-recognized sensitivity to beyond standard model (BSM) physics [1] and magnetic moments being a probe of non-pointlike character of quarks [2]. Both chromomagnetic and magnetic dipole moments are also sensitive to BSM input from physics at a mass scale beyond m_t [3].

For a pointlike spin-1/2 top quark in the heavy quark limit $m_t \gg m_h$, the $h \rightarrow gg$ amplitude and decay rate are derived from the effective Lagrangian (see Eqs. (2) & (9) of [4], also Eq. (27) of [5])

$$\mathcal{L}_{hgg} = -b_0(\kappa_t) \frac{\alpha_s}{2\pi} \frac{h}{v} \frac{1}{4} \text{Tr} G^{\mu\nu} G_{\mu\nu} \quad (1)$$

where b_0 is the QCD β -function coefficient arising from the top contribution to vacuum polarization, which is a function of quark chromomagnetic factor κ_t , but is usually evaluated for the case of $\kappa_t = 2$. h is the dynamical Higgs field, $v = 246.2$ GeV the Higgs vacuum expectation value, $\alpha_s = g_s^2/4\pi \simeq 0.108$ the QCD coupling constant at top-quark scale, and $G_{\mu\nu} \equiv G_{\mu\nu}^a t^a$ the gluon field strength tensor.

In this work, we obtain $b_0(\kappa_t \neq 2)$ in Eq. (1) explicitly as a function of the top quark chromomagnetic ratio and discuss the effect $b_0(\kappa_t \neq 2)$ has on the leading order $h \rightarrow gg$ decay amplitude. The chromomagnetic factor κ_t is the dimensionless parameter controlling the size of the chromomagnetic moment

$$\tilde{\mu}_t = \frac{\kappa_t}{2} \frac{g_s}{2m_t}, \quad (2)$$

where $m_t = 173.5$ GeV is the top mass. $\tilde{\mu}_t$ is defined paralleling the QED magnetic moment, assigning to κ_t the role of a chromomagnetic “ g -factor.” Correspondingly, in a theory describing the top with the Dirac Lagrangian and at tree-level $\kappa_t = 2$, as seen by squaring the Dirac operator $\gamma_5 \gamma^\mu \Pi_\mu = \gamma_5 \gamma^\mu (i\partial_\mu + g_s t^a A_\mu^a)$ with Π the Hermitian momentum operator with minimal gauge coupling in the covariant derivative.

The ‘conventional’ anomalous $\kappa_t \neq 2$ arises from quantum corrections within the SM. The unit strength the top-Higgs coupling (expressed by the high top mass) offers a unique opportunity for ‘conventional’ modifications of κ_t . Considering the fragmentary knowledge of how either SM or BSM physics modifies κ_t , we consider the anomalous chromomagnetic moment a parameter that can be determined from experiment [6–9] and from theoretical studies [10–12].

Top quark $b_0(\kappa_t)$ function: Figure 1 exhibits the diagrams describing top and bottom quark fluctuations leading to the Higgs-two gluon effective coupling. The top quark contribution is related to its contribution to the renormalization group β -function of the QCD coupling [4, 5], manifested in Eq. (1) by b_0 being leading order coefficient in the perturbative expansion of the β -function,

$$\beta \equiv \lambda \frac{\partial \alpha}{\partial \lambda}, \quad \beta(\alpha) = -\frac{b_0}{2\pi} \alpha^2 + \dots \quad (3)$$

We take the bottom quark contribution as given by the SM, considering modification of the bottom chromomagnetic moment likely to be smaller. For this reason, only standard vertices appear in figure 1(b).

To calculate b_0 with the top chromomagnetic moment as a free parameter, we use a second-order theory of fermions, which has been investigated in context of QED perturbatively [13] and non-perturbatively [14]. In this approach,

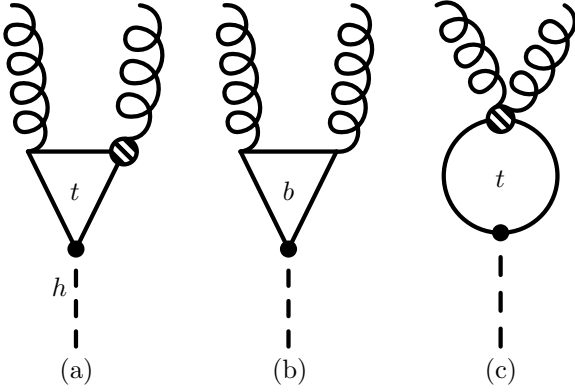


Figure 1: The dominant leading-order diagrams generating the effective Higgs-to-two gluon hgg coupling: a) top and b) bottom quark loops. One top-gluon nonperturbative vertex has a shaded circle to signify that we consider a general value of the top chromomagnetic moment. c) The 2nd order theory additional diagram including the two top two gluon vertex.

the top is described by the (effective) Lagrangian

$$\mathcal{L}_{\text{top}} = \bar{\psi} \left(\Pi^2 - m_t^2 - \frac{\kappa_t g_s G^{\mu\nu} \sigma_{\mu\nu}}{2} \right) \psi \quad (4)$$

where $\sigma_{\mu\nu} = (i/2)[\gamma_\mu, \gamma_\nu]$. A second-order theory has been discussed for calculating helicity amplitudes including top anomalous dipole moments, and Eq. (27) of [15] makes it clear that Eq. (4) would be connected to the first order (Dirac) theory by a non-perturbative summation within QCD.

When developing the perturbation expansion, the 2nd order theory Eq. (4) generates a two-top to two-gluon vertex and hence an additional diagram (c) in figure 1. The added complexity of the perturbation theory is avoided by using the low energy theorem Eq. (1) [4, 5]. Note that in the 2nd order theory, no new scale has appeared to complicate the renormalization group running or possibly limit the validity of our result, because the coefficient of the magnetic moment operator is dimensionless $\kappa_t/2$.

The one-loop contribution to the QCD β -function can be obtained using the external field method [16, 17]. At one fermion loop, that calculation is parallel to the one performed in QED. One need only modify the QED result by introducing a factor 1/2, which arises from the trace of two Gell-Mann matrices at the top-gluon vertices $\text{tr}(t^a t^b) = \delta^{ab}/2$. Following the steps in [16], one arrives at

$$b_0(\kappa_t) = -\frac{2}{3} \left(\frac{3}{8} \kappa_t^2 - \frac{1}{2} \right) \quad (5)$$

The $-2/3$ factor separated in front is the well-known value of b_0 for $\kappa_t = 2$. Eq. (5), normalized by $b_0(2) = -2/3$, is shown in Fig. 2.

The functional dependence on κ_t has been obtained in the QED calculation using two independent methods: perturbative computation [13] and external field method [14]. The latter method has been extended to large values of $|\kappa_t| > 2$ where $b_0(\kappa_t)$ is periodic outside the domain $-2 <$

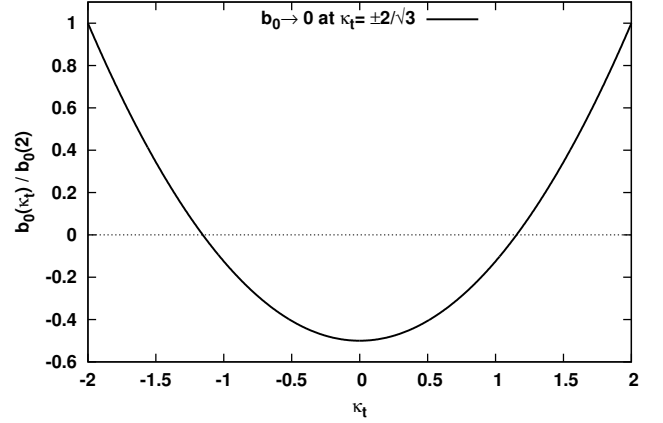


Figure 2: The b_0 coefficient of the QCD β function contributed by the top quark normalized to its value at $\kappa_t = 2$.

$\kappa_t < 2$. Naive expectation is that the QCD b_0 coefficient is similarly a periodic function of κ_t , in which case $\kappa_t = 2$ is a maximum of b_0 and consequently also of the $h \rightarrow gg$ amplitude. The behavior of $b_0(\kappa_t)$ for $|\kappa_t| > 2$ requires further study beyond the scope of this paper, and seeing that perturbative evaluation within the SM suggests that $\kappa_t - 2 < 0$ (Eq. (10) below), we continue assuming this is the interesting case.

An important feature of $b_0(\kappa_t)$ is that it changes sign at $\kappa_t = \pm 2/\sqrt{3}$ and hence is positive for $|\kappa_t| < 2/\sqrt{3}$. This effect is due to the decreasing strength of the paramagnetic spin term as κ_t diminishes [18]. If in fact $|\kappa_t| < 2/\sqrt{3}$ the pattern of interference between the top quark and the lighter quarks changes: for all other quarks b, c, \dots the perturbatively evaluated triangle diagram Figure 1(b) yields a positive amplitude, opposite in sign to the top loop. If the top loop contribution is positive, along with all the other quark loops, the overall Higgs-gluon coupling will have the “wrong sign”, a possibility recently noted may have a destabilizing impact on the SM [19].

κ_t dependent decay width: At leading order, the $h \rightarrow gg$ decay width is (see Eq. (21) of [5])

$$\Gamma(h \rightarrow gg) = \left| \sum_{q=t,b,\dots} F_q \right|^2 \left(\frac{\alpha_s}{4\pi} \right)^2 \frac{m_h^3}{2\pi v^2} \quad (6)$$

where F_q is a complex form factor for each quark, in general a function of the ratio $x = 4m_q^2/m_h^2$. Calculating the decay rate from \mathcal{L}_{hgg} and comparing to Eq. (6), one finds the form factor F_t goes into the β -function coefficient. With the Higgs mass at $m_h \simeq 125.5$ GeV, evaluating the amplitude with $F_t \rightarrow b_0$ means an error of a few percent relative to the result from the exact loop amplitude [4, 5]. Thus, although the ratio $m_h^2/4m_t^2 \simeq 0.13$ is not especially small, the heavy quark limit allows a good estimate of the leading-order contribution. Higher order QCD corrections to Eq. (6) are significant, next to leading order diagrams contributing $\sim 65\%$ enhancement [5].

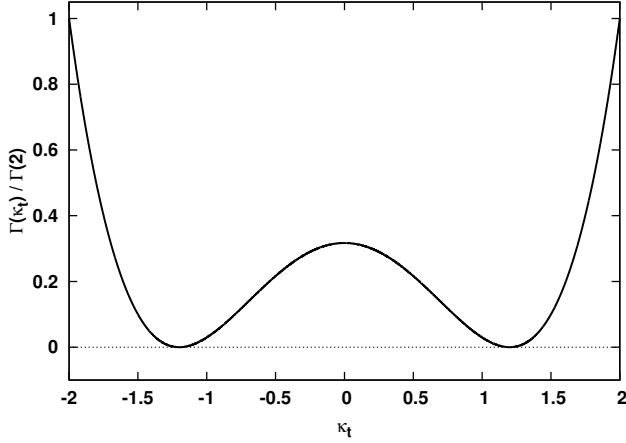


Figure 3: Higgs to two gluon $h \rightarrow gg$ decay rate normalized to its value at $\kappa_t = 2$.

Recent calculations have been extended to next-to-next-to-leading order including soft gluons to next-to-next-to-leading logarithms [20]. Electroweak corrections amount to a couple of percent [21].

The bottom quark vacuum fluctuation is included, because it makes a contribution to the amplitude opposite in sign to the top, and consequently interference with top quark amplitude is important. Neglecting charm and lighter quarks, which make tiny quantitative changes compared to bottom, the total form factor in Eq. (6) is

$$\sum_q F_q \simeq F_t + F_b = b_0(\kappa_t) + F\left(\frac{4m_b^2}{m_h^2}\right) \quad (7)$$

The β -function coefficient b_0 is given by Eq. (5) and the bottom contribution is the $x = 4m_b^2/m_h^2$ dependent function (see Eq. (21) of [4] or Eq. (3) of [5]),

$$F(x) = \begin{cases} x \left(1 - \frac{1-x}{4} \left(\ln \frac{1+\sqrt{1-x}}{1-\sqrt{1-x}} - i\pi \right)^2 \right) & x < 1 \\ x((x-1) \arcsin^2(x^{-1/2}) - 1) & x \geq 1 \end{cases} \quad (8)$$

For $m_b = 4.5$ GeV, F_b is opposite in sign and about 17 times smaller than the top quark contribution (at $\kappa_t = 2$).

Fig. 3 shows the κ_t dependence of the total $h \rightarrow gg$ decay rate, normalized to its value at $\kappa_t = 2$,

$$\frac{\Gamma(\kappa_t)}{\Gamma(\kappa_t \rightarrow 2)} = \frac{|b_0(\kappa_t) + F(x)|^2}{|b_0(2) + F(x)|^2} \quad (9)$$

The rate falls quickly for $\kappa_t < 2$ (see below Eq. (10)), and for $|\kappa_t| = 1.22$ the leading order decay rate goes to zero. In reality, Γ probably does not vanish exactly due to higher order diagrams becoming the dominant contributions—recall that QCD corrections alone are known to be large at next-to-leading order. Adding the contributions of the other light quarks c, s, \dots would, however, only change the value of κ_t at which the leading order $\Gamma \rightarrow 0$.

Experimental considerations: Our approach computing with κ_t as a parameter and obtaining an analytic result allows input from constraints derived from independent experiment (e.g. hadronic top pair production) and facilitates study of standardized contributions from beyond Standard Model physics. Estimates of κ_t based on various SM and BSM input assumptions can be found in literature.

The one-loop perturbative SM prediction is (see Eq. (4) of [12])

$$\kappa_t - 2 = -5.6 \cdot 10^{-2} \quad (10)$$

which would lead to a 9% decrease in the Higgs decay rate. However, higher order QCD and virtual Higgs can yet make equally important and coherent contributions to the amplitude resulting in a possible major departure of the $h \rightarrow gg$ decay rate from prior expectations. Thus irrespective of the eventual presence of new physics, we believe that the expected magnitude of the decay of Higgs to gluons is significantly modified. Conversely, the measurement of partial branching ratio of $h \rightarrow gg$ would amount to a step towards the measurement of the top-quark chromomagnetic moment.

Constraints on κ_t have been considered already in the study of the top quark production [6–8]. According to Eq. (18) of [9], present data sets a bound $|\kappa_t - 2| < 0.2$, which could mean that the decay rate is reduced by up to 25%. Considering that many more diagrams (4-gluon, 6-gluon... fusion) contribute to top production, this is just a first step in a more elaborate evaluation of the role of κ_t in top production. The radiative decay $b \rightarrow s\gamma$ has also been discussed as providing constraints on κ_t [10, 11].

Having shown that $\kappa_t \neq 2$ induces a dramatic modification the $h \rightarrow gg$ decay rate, we now discuss a means of seeing this effect in experiment. We argue next that, for Higgs produced at rapidity $|y| > 2$, the $h \rightarrow gg$ decay hadron jets may be separable from randomly correlated directly produced QCD jet background. Moreover, if $h \rightarrow gg$ is visible, it is sure that another reference decay channel with which one can compare is visible as well allowing to measure the relative strength of the glue decay channel.

The two decay gluons produce two hadron jets back-to-back in the rest frame of the Higgs carrying the significant invariant mass $\simeq 125.5$ GeV. While this characteristic may be insufficient to separate the Higgs from the random hadron jet background at central rapidity, we suggest to consider events sourced by Higgs particles having rapidity $|y| > 2$, that is Lorentz factor $\gamma > 3.8$. These may be numerous enough given that $\gtrsim 25\%$ of Higgs are expected to be produced with $|y| > 2$ according to Fig. 3 of [23]. The total energy of the CM frame of back-to-back jets is boosted by γ towards and beyond $\gamma m_t \geq 500$ GeV. Since the transverse momentum of the produced Higgs is expected to be small (a majority of events at $p_T \lesssim 0.3m_H$ [23]), the total transverse momentum of the jets will be on average an order of magnitude smaller compared to the boosted longitudinal momentum. The mo-

momentum of $|y| > 2$ Higgs decay jets is conveniently projected along the collision axis.

Higher order processes contribute to the probably significantly smaller (incoherent) yield of 4-gluon, 6-gluon, etc. decay events which will depend on the chromomagnetic moment as well. If the suppression of the 2-gluon decay is large, further consideration should be given to these multi-jet decays with regard to their sensitivity to the chromomagnetic moment. However, their yield is smaller and the experimental detectability diminishes due to reduced correlation between decay jets creating a higher random jet background.

Discussion and conclusions: Though Higgs-two-gluon decay is challenging to measure, our study highlights the significant fundamental interest in arriving at a precise result for this decay channel. The motivation arises from the connection made here between the Higgs-two-gluon decay rate and the top quark chromomagnetic moment, which among today-measurable parameters is arguably the most sensitive to BSM effects. For example, a common change in magnitude of the *magnetic moment* of all quarks Eq. (2) would most influence the Bohr magneton of the heaviest quark, since its natural scale $1/m_t$ is smallest by a large factor.

This study extends our previous work on the electromagnetic top magnetic moment and its effect on Higgs-two-photon decay, which also depends on the top-quark vacuum fluctuations [22]. The sensitivity of the respective processes and the experimental opportunity differ: The two photon decay is a tiny but well visible 0.2% contribution to the total Higgs decay, in which process the top-quark plays subordinate role to the W -fluctuations. Even so, modification of the top magnetic moment can lead to significant enhancement of the decay process. In comparison, the SM prediction is that a scalar Higgs at mass $m_h \simeq 125.5$ GeV decays in about 8.5% of cases into two parallel polarized gluons [24] which turn into hadron jets. The two gluon decay is thus relatively large and sensitive, because modifications of the now dominant top-quark can drastically reduce the decay rate. Change of top chromomagnetic properties can thus affect the total decay rate by up to 8%.

The Higgs production process by gluon fusion also involves heavy quark vacuum fluctuations and is subject to modification induced by $\kappa_t \neq 2$ we described. However, the magnitude of the modification of Higgs production cross section does not follow directly from our present considerations: higher order $2n$ -gluon fusion processes with $n > 1$ are important and contribute coherently. A considerably more detailed investigation is needed to understand the influence of κ_t in the realm of Higgs production.

To summarize, we have argued that the chromomagnetic moment of the top quark offers an opportunity to search for quark compositeness and BSM physics. We have considered the top chromomagnetic moment κ_t a parameter, and have shown the dependence of the leading order

Higgs-two-gluon interaction \mathcal{L}_{hgg} on κ_t . Due to the dominant role of the top in the effective Higgs-gluon interaction, we obtain a large sensitivity of the Higgs-two-gluon $h \rightarrow gg$ decay to the top chromomagnetic moment: even the one-loop SM estimate of $\kappa_t = 2$ leads to a 10% suppression of the 2-gluon decay channel, and a much larger effect could result from quark compositeness or other BSM physics. Conversely, absence of visible effect may push the associated BSM energy scale up significantly due to the hyper-sensitivity of particle magnetic moment to new physics [2, 3]. Finally, we have discussed potential opportunities to search for the 2-gluon decay process among correlated high energy hadron jets originating from $|y| > 2$ Higgs production.

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